

THE EFFECTS OF COLD-WORKING ON THE ELASTIC PROPERTIES OF STEEL

BY

J. A. VAN DEN BROEK

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN THE
UNIVERSITY OF MICHIGAN



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INTRODUCTION.

STEEL has been intensively studied, especially during the last thirty years. It would appear, however, that most of the research on steel has been conducted by chemists and metallurgists, and has thus been confined to the chemical and metallurgical laboratory. From the metallurgical and chemical points of view, therefore, the subject of "The Effects of Cold-Working on Steel" has been profoundly studied during the last fifteen years, especially in England, by such men as Beilby, Rosenhain, Ewing, and Humphrey. The study of the effects of cold-working on the physical properties of steel, however, seems to be limited to J. Bauschinger,¹ James Muir,² and to the recent work by the United

¹ *Mitteilungen aus dem Mechanisch-Technischen Laboratorium der K. Technischen Hochschule in München*, 1886, vol. 13.

² "On the Recovery of Iron from Overstrain," *Philosophical Transactions of the Royal Society of London*, 1900, vol. 193.

States Testing Laboratory at the Watertown Arsenal, Massachusetts.¹ It is stated the tests at the Watertown Arsenal are being continued so that additional information may be expected in the near future.

Bauschinger's work of 1886 to-day stands out pre-eminently as the most advanced treatise on the subject. He experimented mostly on mild steel, and studied the effects of strain in tension and compression on the elastic properties of steel in tension and compression. He also studied the effects of ageing, and to a slight extent the effect of tempering on cold-worked steel.

Muir, who also worked on mild steel, confined himself largely to hysteresis, the effects of cold-stretching, and the effects of tempering at low heats, such as the temperature of boiling water, which he studied in detail.

At the Watertown Arsenal, as stated in its publications to date, experiments with 3.25 per cent. nickel steel were carried out, and the effects of cold-stretching on the elastic properties in tension and compression were studied. Some attention was paid to ageing but none to tempering.

Commercially, the term cold-working ordinarily refers to cold-drawing, rolling, or twisting. In this paper the term will be applied to any process which causes permanent change of shape of steel at a temperature below the critical temperature. An attempt has been made to study the subject in its broadest aspect. Steel has been cold-stretched, cold-compressed, and cold-twisted, and each one of these three kinds of cold-working has been studied as to its effects on the elastic properties of steel in tension, compression, and torsion.

In addition, the effects of tempering cold-worked steel at such low temperatures as the temperature of boiling water have been investigated in connection with ageing.

MATERIALS AND APPARATUS.

The material considered in this paper has been a low carbon, hot-rolled, mild steel. The chemical composition of a few of

¹ "Test of Metals," 1915.

the bars tested is as follows, different bars being designated by different letters :

TABLE I.

Letter.	C.	Mn.	Si.	Ni.	Cr.	S.	P.
d	0.21	0.40	trace	nil	nil	0.040	0.012
p	0.16	0.27	..	..	..	0.063	0.094
K	0.16	0.26	0.018	..	..	0.025	0.006
w	0.26	0.34	0.009	..	..	...	0.017
Balls	0.95	0.37	0.27	..	0.65	0.025	0.025

The tests have all been made by the author in the Testing Materials Laboratory of the University of Michigan. The machines used were one 50,000-pound capacity Riehle tension and compression machine ; one 200,000-pound capacity Riehle tension and compression machine, and one 232,000 inch-pound capacity Olsen torsion machine.¹

It should be borne in mind that these testing machines are straining machines and not loading machines. Strain is here defined as deformation per unit of length, stress as load per unit of area. For example, in conducting a tensile test, after placing the specimen in the machine, the machine is run at a uniform speed. The specimen is strained (elongated) proportionally to the speed of the machine. At first, within the elastic limit, the stresses increase at the same rate as the strains, and correspondingly the loads, which are measured by the machine, increase uniformly. After passing the elastic limit, although the specimen continues to be strained at the same rate, the stress increments are no longer proportional to the strain increments, and the loads registered by the machine ceases to increase uniformly.

TESTS.

The tension tests require little explanation. The specimens were tested by the usual method and gripped between wedge grips. For some purposes the threaded grips may be superior to the wedge grips. However, on account of the large variety of specimens tested and the desire to test the same specimens

¹ Moore, "Materials of Engineering," p. 159.

alternately in tension, compression, and torsion, it was necessary to use wedge grips, and it was found that, with a reasonable amount of care, the experimental error could be reduced to a minimum.

The compression tests have all been performed on specimens not less than $9\frac{1}{2}$ inches and not more than 20 inches in length. The ends of each compression specimen were faced so as to make them perfectly flat and parallel. Plate I. shows a $\frac{3}{4}$ -inch square

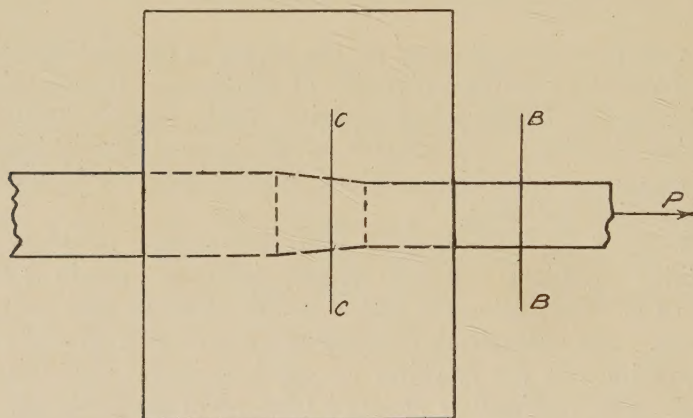


FIG. 1.

twisted bar in the 50,000-pounds capacity machine ready to be tested in compression.

Possibly some will question the advisability of using such relatively long compression specimens, *i.e.* for which the ratio l/r is so high. Most experimenters, it seems, have confined themselves, in compression tests, to short columns, sometimes only 1 inch long, presumably to obviate possible errors due to buckling. It appears that one may anticipate two errors in compression tests, one as the result of buckling and another as the result of friction between the bearing blocks and the ends of the specimen. The latter error, it seems, is nearly always present, and its disturbing effect increases as the length of the test specimen decreases. The effect of buckling, although it plays a very important part in structural columns, it is believed may be neglected in laboratory

tests, provided the specimen is carefully prepared and the test carefully performed. When buckling does occur, the error is accumulative and marks the end of the test. Similarly, if one is able to load in compression an unbraced specimen 1 inch square and 20 inches long, to a stress of 80,000 pounds per square inch, as illustrated in curves No. 75(f), Diagram II., and curve No. 175(m), Diagram V., and have such specimen support a load of 75,000 pounds indefinitely, one may conclude that the effect of buckling is nil. The horizontal part of curve No. 17(d), Diagram II., illustrated how a compression specimen sometimes may be strained, under a constant load, a considerable distance after the elastic limit is passed, without buckling. Ordinarily, however, buckling sets in as soon as the elastic limit is reached, as is brought out by the fact that most of the curves on Diagram II. and Diagram V. drop rapidly after the elastic limit is passed.

MEASUREMENTS.

The angular strains in the torsion tests were measured by an arc and pointer clamped 12 inches apart on the specimen.

The linear strains in the tension and compression tests were measured with a Berry strain gauge.

The Berry strain gauge is shown in Plate I. clamped to a compression specimen ready for a test. It consists of two steel pivots in a steel frame 8 inches apart. One pivot is fixed while the other is part of a bent lever, and rotates freely in a V groove. The lever extends inside of the steel frame to a point underneath an Ames dial. The Ames dial registers movement of the end of the lever to $\frac{1}{10,000}$ of an inch. Referring to Plate I., the top pivot is fixed while the lower pivot is free to move. As the specimen is compressed the two pivots move closer together, and the lever of which the lower pivot is a part moves outward and reacts on the Ames dial at a point inside the steel frame. Previous to placing the strain gauge, two punch marks are made on the specimen 8 inches apart, with a marker the points of which exactly correspond to the points on the pivots of the strain gauge. In order to avoid bending the specimen as the clamp is tightened, a steel plate, slightly sprung, is slipped between the specimen and the clamp. When the strain gauge is clamped on, this

bridge, shown in Plate I., carries the reaction of the clamp to two points exactly opposite the pivots of the strain gauge.

One objection commonly made to the arrangement as described is that the gauge is clamped to but one side of the specimen. This criticism is no doubt qualitatively justifiable. However, experimental error is inevitable with any instrument. It is merely a question as to whether the experimental error seriously impairs the conclusions drawn from the tests. With careful manipulation it appears that this error dwindles into insignificance. In fact, the curves faithfully plotted from laboratory sheets speak for themselves.

THE COLD-WORKING.

The cold-stretching was accomplished in the tension machine by stretching specimens beyond their original elastic limit any desired amount.

The cold-compressing was accomplished in especially designed braces. Plate II. shows a 1-inch square specimen in the 200,000-pounds capacity Riehle tension and compression machine, ready to be compressed. One-half of another brace, the one next smaller in size, is depicted to the left in Plate II. to show the V groove and the steel lining of the wooden braces, which proved necessary. A set of braces varying by 1 inch in length from 21 inches down to 16 inches were especially designed for the cold-compression process. If, for example, a cold-compressed specimen was desired long enough after cold-compressing to be used in a tension test, a bar of mild steel 1 inch square, 22 inches long, and with both ends faced, was selected. This specimen was first oiled and then clamped in the 21-inch brace, leaving $\frac{1}{2}$ inch of steel projecting outside of the brace at each end. The clamps were very thoroughly tightened to ensure perfect bearing along the entire length of the bar, after which cold-compressing could be commenced. As the compression progressed the specimen naturally increased in size transversely, but this swelling was easily taken up in the wood and in the steel clamps. After compressing a 22-inch specimen to 21 inches in the 21-inch brace, the load was released, the braces taken off, and the operation repeated in the 20-inch brace. In this manner a bar, 22 inches

long, could be shortened 3 inches, while maintaining a perfect alignment throughout the cold-working process. The braces were purposely designed long so that the cold-compressed bars might subsequently be tested in tension and have sufficient length to allow space for the grips of the machine and for the strain gauge.

The cold positive twisting was easily accomplished in the 232,000 inch-pound capacity Olsen torsion machine. Difficulty occurred, however, as soon as twisting in a negative direction was attempted. In the first trial the torsion machine was lifted off its base and the specimen twisted out of alignment, because the machine was not designed to perform negative twisting. By providing a suitable steel framework for the recording end of the torsion machine and weighing it down with a few tons of cast iron, 2-inch diameter round bars were successfully cold-twisted in two directions.

Tension and compression may be considered as stresses of the same kind but opposite sign. We might intelligibly distinguish between them as one being a positive stress and the other a negative stress. Similarly, right-handed twisting and left-handed twisting may be considered as of the same kind but opposite sign, and for the purposes of this investigation we shall thus distinguish between positive and negative twisting. However, only a positive torque could be measured on the machine.

DISCUSSION OF THE DATA.

The elastic properties of steel considered in this paper are of three kinds—namely, tension, compression, and torsion (shear). Four different kinds of cold-worked steel were each tested for these three kinds of elastic properties—namely, steel as received, steel cold-stretched, steel cold-compressed, and steel cold-twisted.

Two hundred and fifteen specimens were tested, and curves were plotted for each test. Rather than reproduce over two hundred sheets of tabulated data, only curves are here given, and rather than reproduce over two hundred curves, many of which are duplicates, only representative curves have been selected and grouped together for purposes of comparison. Of

course, curves differed in different tests. Not always, however, have the most nearly perfect curves been selected for reproduction, but rather curves which were to be compared with one another were obtained, as much as possible, from specimens cut from the same bar, and then plotted on the same plate. No curve is here given without having the properties which it suggests substantiated by several independent tests on different material. If some of the stress-strain curves appear unusually accurate straight lines, they are nevertheless faithful reproductions of laboratory sheets, and it is from the sensitiveness of the curves and the slight deviations from straight lines which one may distinguish, that the author derives his confidence in the significance of the results. As this paper is concerned with the elastic properties of steel, none of the curves are continued to the breaking point. The last point on each curve marks a point well beyond the elastic limit where the strain gauge was removed. Without exception all curves were plotted from the zero point, although the danger of experimental error under low loads, before the test is well under way, is very great. If the specimen is slightly bent, in a tension test, the first increments of load will tend to straighten it, which will cause an erroneous reading of the strain gauge. Possibly the wedge grips do not pull evenly during the first stages of the test, which again may cause an error in strain-gauge reading. In a compression test, the smallest eccentricity in loading, or a minute obstruction between the specimen and the bearing blocks, will cause an erroneous reading of the strain gauge until an adjustment has been made, after which the strain gauge will record the true elastic behaviour of the specimen. For this reason it is believed best not to attach any special importance to slight positive or negative bends of the curves within low stress values. The essential feature to consider in this discussion would seem to be whether the stress-strain curves beyond stresses of 5000 pounds per square inch are straight lines or not.

A great deal has been written about the definition of elastic limit and yield point of steel.¹ Without presuming to take sides in the different arguments, elastic limit in this paper is understood to be the stress at which the curve first deviates from a

¹ Howard and Linch, *Proceedings of the American Society for Testing Materials*, 1915-1916.

straight line. In nearly all cases the point is quite clearly defined on the curves.

By yield point is meant the stress at which the steel begins to deform very rapidly under very small increments of stress. Although not so clearly defined as the elastic limit, it is nevertheless necessary to refer to it occasionally.

The meaning of the different numbers and letters on different curves is explained as follows. The numbers refer to the order in which the tests were made; the letters in brackets after each number refer to the bar from which the specimen was cut. If the elastic properties of specimens were to be compared with one another, the specimens were, as much as possible, cut from the same bar, and thus, although having a different number, are designated by the same letter in brackets following the number.

The curves are to some extent self-explanatory. The type of test they represent is printed on each curve, as much as possible, in order that the diagrams may be studied independently of the text. All curves on each diagram, although representing specimens cold-worked in different manners, represent one kind of test only—namely, tension, compression, or torsion. The only exception is in Diagram IX., where one compression curve is shown along with two tension curves. The diagrams showing tension and compression curves need little explanation. The stress is the load per unit area; the strain is the deformation (lengthening or shortening) per unit of length. The degree of cold-stretching or cold-compressing is expressed in percentage, which was obtained by computing the difference between the original and the final gauge length of the specimen and dividing that difference by the original gauge length.

The slope of stress-strain curves is a measure of the modulus of elasticity, or of rigidity. All curves with the same slope, therefore, have the same modulus of elasticity or modulus of rigidity. Torsional stress-strain curves are frequently seen plotted with the torque as abscissa and the angle of twist as ordinate. Since the torque varies as the cube of the diameter and the angle of twist varies inversely as the diameter, one naturally obtains in such a case two entirely differently sloping curves for two shafts that are essentially the same and differ only in diameter. The curves in Diagrams III. and VI. are all plotted

from data reduced to units corresponding to the units plotted on the tension and compression stress-strain curves—namely, stress at the extreme fibre figured from the formula $f = \frac{16 T}{\pi d^3}$

and strain at the extreme fibre from the formula $\delta = \frac{\phi \times r}{l}$.

With these units torsional stress-strain curves will have the same slope when the modulus of rigidity of different specimens is the same, regardless of differences in diameters of the shafts. In an attempt to reduce the degree of cold-twisting to standard units, the degree of cold-twisting of specimens, the stress-strain curves of which are plotted on Diagram VI., is expressed in a percentage as radians of twist per radian of length. Thus a 3-inch shaft twisted one revolution in 12 inches would be said to be cold-twisted, $\frac{2\pi \times 1.5}{12} = 0.787$ radians per radian = 78.7 per cent.

On Diagrams III., IV., V., VI., and IX. the origin for each curve was shifted so as to avoid overlapping of curves.

Diagrams I., II., and III. are similar and should be studied in conjunction. Diagram I. shows steel cold-worked in four different ways and subsequently tested in tension. Diagram II. shows a similar set of specimens tested in compression, and Diagram III. shows a third set cold-worked in four different ways but tested in torsion.

Curve No. 25(d), Diagram I., shows a stress-strain curve for a bar of mild steel "as received," tested in tension. By "as received" is meant the state of the steel in which it was received at the laboratory, viz. hot rolled and covered with mill scale. It may be noticed that the major part of curve No. 25(d) is horizontal until it runs off the plate. This of course does not mean that the steel broke at that point or that the steel could be strained indefinitely without producing any increase of stress. In order to plot curve No. 25(d) to the same scale, until its maximum stress was reached, we should require a diagram ninety times the length of Diagram I. After the data for curve No. 25(d) were obtained, the strain gauge was removed and the bar was continued to be strained until a maximum stress of 58,800 pounds per square inch was reached. It was then

taken out of the machine, boiled for fifteen minutes, and tested again as No. 27(d). Note that the elastic limit of No. 27(d) comes at about 66,000 pounds per square inch, or 12 per cent. beyond the stress at which the cold-stretching was discontinued.

Also note the high ductility, 64·7 per cent., as expressed in percentage reduction of area, coincident with this high elastic limit. In fact, the effects of cold-working on the elastic properties of steel seem to be independent of the stresses involved in the cold-working process, but seem to be a function of the strains produced in cold-working, regardless of how such strains are brought about. Curve No. 22(d), Diagram I., and curve No. 21(d), Diagram II., were obtained from a piece of steel cut from the same stock as No. 25(d) and No. 27(d), cold-twisted, then cut in two, and one part tested in tension as No. 22(d), Diagram I., and the other part tested in compression as No. 21(d), Diagram II. These two curves are very similar indeed, which suggests that cold-twisting modifies the tensile elastic properties of steel similarly to the way it modifies its compressive elastic properties.

Curve No. 75(f), Diagram II., was obtained from a specimen cold-compressed 15·6 per cent., then boiled, and then tested in compression. It is seen that, just as cold-stretching raises the elastic limit of steel in tension, so cold-compression raises the elastic limit of steel in compression.

Curve No. 80(m), Diagram I., was obtained from a specimen cold-compressed 8·1 per cent., tempered in boiling water and tested in tension. Curve 77(d), Diagram II., was obtained from a specimen cold-stretched 24·1 per cent., boiled and tested in compression. Both curves show an elastic limit of the same value as the original elastic limit but a somewhat raised yield point.

Diagrams IV., V., and VI. were compiled for the purpose of bringing out the significance of time and temperature effects on cold-worked steel.

It is seen from curves No. 171(p), No. 78(d), and No. 172(p), Diagram IV., from curves 176(m) and 175(m), Diagram V., and from curves 182(v) and 183 (v), Diagram VI., that if steel is tested in the direction in which it was cold-worked, very soon after cold-working, the elastic limit is lowered below the original elastic limit, often down to zero, and the yield point comes about at

the stress at which cold-working was discontinued. If the specimen is aged for a short time (curve No. 78(d), Diagram IV.), the yield point is raised but the elasticity is not perfected; if the specimen is tempered, however, at a heat of about 100°C . or more, the elasticity of the steel is perfected and the elastic limit is raised from 10 per cent. to 20 per cent. beyond the stress at which cold-working was discontinued. Curves of aged specimens, other than the one here shown (No. 78(d), Diagram IV.), have shown occasionally greater improvement in the elastic properties of steel, as the result of ageing, but never have the effects of ageing a hundred days proved equal to the effects of tempering. It is believed, however, that if sufficient time is allowed, ageing will perfect the elasticity of cold-worked steel to the same extent that tempering at low temperature does.

After the diagrams were made up, a possible source for misinterpretation was noticed in the way curves A, No. 171(P), No. 78(d), and No. 172(P) are shown in relation to one another on Diagram IV. It is to be noted that No. 171(P) and No. 172(P) are strictly comparable. They were of the same specimen, in one case tested immediately after cold-working; in the second case tested after tempering for a few minutes at 100°C . Curve No. 78(d) was of an entirely different specimen, and is strictly comparable to curve No. 27(d), Diagram I. In its position on Diagram IV. it shows clearly that ageing 114 days did not perfect its elasticity beyond its original elastic limit; that is to say, the curve approaches the original tangent but does not coincide with it. It might, however, also lead one to suppose that ageing did not raise the yield point. This is not the case, as a similar specimen without ageing not only departed further from a straight line, but had its yield point 10 per cent. lower; and a third specimen, cold-stretched exactly the same amount and boiled, was like curve No. 27(d), Diagram I., with its curve perfected but its yield point at about the same value as that reached by ageing 114 days.

On the specimens tested in a direction opposite to the direction of cold-working (curves No. 114(t), 115(t), and 112(t), Diagram IV., curves 180(w), 178(w), and 177(w), Diagram V., and curves 146(v) and 147(v), Diagram VI.) the effect of ageing and tempering is seen to be even more pronounced. When a specimen is tested

within ten minutes after cold-working, in a direction opposite to that in which it was cold-worked, the elastic limit is seen to be zero (curves 114(t), Diagram IV., 180(w), Diagram V., and 146(v), Diagram VI.). If aged for a few days, the elasticity is partly restored, but in no case comes up to the original elastic limit (curves No. 115(t), Diagram IV., and No. 178(w), Diagram V.). If heated to 100°C . or a little more, the elasticity of the specimen is perfected up to or somewhat above the original elastic limit (curves No. 80(m), Diagram I., No. 77(d), Diagram II., No. K.65, Diagram III., No. 112(t), Diagram IV., No. 177(w), Diagram V., and No. 147(v), Diagram VI.).

Curve No. 181(m), Diagram V., shows the elastic properties of steel which was cold compressed 11.6 per cent., then boiled, then cold stretched 7.5 per cent., then boiled and subsequently tested in compression.

The horizontal portion of the stress-strain curves, so pronounced in many of the curves, may be explained as follows. The engineer defines elastic limit as the stress at which the stress-strain curve departs from a straight line. The metallurgist defines it as the stress at which some of the steel grains begin to break up (grain failure along slip bands). The two values exactly coincide. The breaking up of the crystals, however, requires time and energy. In a bar machined down in the middle it usually begins in the centre. In a bar of mild steel gripped in wedge grips, it always begins between the wedges, because the strain conditions at that point are a maximum, being the result of the combination of high compression stresses, due to the wedge grips, and high tensile stresses, due to the machine loading. If the straining (elongating) of the specimen continues uniformly, the rupturing of the crystals progresses from the centre towards the ends, or in case of wedge grip arrangement, from the ends towards the centre, under a uniform stress, until all the crystals throughout the entire length of the bar are ruptured, after which the stresses will increase again, more or less proportionally to the rate of increase of the strains. It should be remembered that the modern testing machine is a straining machine and not a stressing machine.

When a bar of mild steel is strained sufficiently to start some of the crystals rupturing and the machine is then stopped, the

specimen will come to equilibrium under a stress such that a little more stress will result in more crystals rupturing; a continuation of that stress or any value less than that stress will leave the specimen in a state with some of its crystal grains ruptured, while others are still intact. This process might be likened somewhat to a line of dominoes set on end. One is caused to fall against an adjoining one, and the whole line will fall as long as conditions are kept constant. When steel is strained and crystals begin to break up, one crystal which fails diverts more stress to its neighbour, this adjoining crystal breaks and in turn causes the next one to break, provided the stresses are kept constant. In the ordinary testing machine, however, the stress cannot easily be kept constant under such conditions. Therefore, when the machine is stopped after the yield point of the specimen is passed, the crystals keep on rupturing for a short time, the specimen correspondingly elongates a little and the load correspondingly drops slightly. The load to which the machine settles down after a specimen of mild steel has been stressed slightly beyond the yield point, but before the crystal grains are disturbed throughout the entire length of the bar, the author has found, corresponds exactly to the elastic limit. If the specimen is being elongated uniformly and continuously, the horizontal part of the curve will run a little higher than if the machine is stopped at intervals and readings taken when the interior of the bar has reached a stage of equilibrium. This is easily explained by the fact that it requires a greater stress to rupture crystals throughout the length of the specimen at a rapid rate than it does at a slow rate.¹

COLD-STRETCHING STEEL DOES NOT LOWER ITS ELASTIC LIMIT IN COMPRESSION.

In nearly all the literature of the last twenty years on the effect of overstrain on steel, the statement occurs that cold-stretching, although raising the elastic limit in tension, lowers the elastic limit in compression.

Rosenhain, one of the most enthusiastic exponents of Beilby's

¹ For beautiful photographs illustrating this point, see *Commission des Methodes d'Essai des Matériaux de Construction, Rapports Particuliers*, tome ii., 1900.

amorphous cement theory, writes in his Introduction to "Physical Metallurgy," Van Nostrand Company, 1914, p. 247 :

"There is one difficulty about the explanation of the hardening of metal by plastic strain, as given by the conceptions explained above, which requires brief mention. This lies in the fact that the hardening produced by plastic strain is, in certain cases at all events, unidirectional. For instance, a piece of steel which has been 'hardened,' i.e. has attained a raised yield point and apparently raised elastic limit, as the result of tensile overstrain, is not really hardened in every way, for, if it is tested in compression, it is found that for stresses of that kind the apparent elastic limit has been lowered, so that the total range of stress of elasticity, from the limit in compression to the limit in tension, has not been materially altered. It is difficult to see how the formation of hard amorphous layers on surfaces of slip can account for softening of the metal in relation to compression while producing hardening as against tension. It may be, of course, that there is something directional about the manner in which the crystalline arrangement is broken up on the slip surfaces, so that a configuration results which allows of slip in one direction but not in another."

And James Muir writes in his article on "The Recovery from Overstrain," *Phil. Trans.*, vol. 193, p. 45 :

"Curve No. 4, further, very clearly shows that tensile overstrain—which raises the yield point in tension—lowers that in compression, or, it may be more definite to say, lowers the load at which any arbitrary contraction occurs. This is in agreement with Professor Bauschinger's conclusion with regard to the elastic limits, viz. that the elastic limit in tension cannot be raised without lowering the limit in compression and *vice versa*. Professor Bauschinger draws a further conclusion from his experiments, namely, that when the elastic limits of a material are varied by overstrain, the range of perfect elasticity seems to remain constant, so that, if the elastic limit in tension be raised, then that in compression is lowered by an equal amount. The author's experiments do not bear this out."

Muir attributes here to Bauschinger the claim that, as the result of tensile overstrain, the elastic limit of steel in compression is lowered an amount equal to the amount its elastic limit in tension

is raised, maintaining constant what is called the elastic range. Although other writers on this subject for the last twenty years almost invariably make this statement, it is usually not accompanied by references to its source, and possibly they are mostly quoting Muir's interpretation of Bauschinger's results.

The author, upon studying Bauschinger's data, was unable to find any such statements. On p. 19, statement 2, of *Mitt. aus dem Mech. Tech. Laboratorium der K. Technischen Hochschule in München* of 1886, Bauschinger states the results of his experiments on the effect of stretching on the elastic properties of steel in tension as follows :

"The elastic limit (in tension) is lowered as the result of stretching, often down to zero, so that the specimen, when it is tested immediately after cold-stretching, has no, or else a very much reduced, elastic limit. During the period of rest which follows the cold-stretching, however, the elastic limit increases again. After several days it attains the stress with which it was cold-stretched, and after a sufficiently long period, certainly after many years, it increases to a value even higher than this stress."

On p. 33 of the same article he says with reference to the elastic properties in a direction opposite to the direction of cold-working :

"As the result of stressing in tension or compression beyond the elastic limit, the elastic limit in compression or tension, respectively, is considerably lowered, so much the more, if the cold-working stresses exceed the respective elastic limits by larger amounts and even comparatively small increments of stress beyond the elastic limits, reduce the elastic limit in opposite direction to zero.

"When an elastic limit, thus lowered in one direction, is raised again by stressing in that same direction, and then exceeded, then, at once, the elastic limit in the opposite direction is again reduced to zero, or nearly to zero.

"Time in these processes is without any effect, or at least has very slight influence. That is to say, the elastic limit in tension or compression, lowered by compression or tension, respectively, is not again raised, at least in the course of three or four days, and in the course of the next few weeks certainly only a little, if at all."

It is interesting that this law of Bauschinger's, laid down in 1886, is essentially confirmed by all subsequent research, and also by the work presented in this paper. The generally quoted statement that stretching steel lowers its elastic limit in compression proportionally to the amount it was stretched beyond its original elastic limit, is therefore not substantiated, neither by Bauschinger, nor by Muir, nor by the author, and the author has failed to discover any original data anywhere which seems to substantiate that contention. The apparent discrepancy between the results of different authors seems to be due to the fact that the significance of ageing and tempering has not always been sufficiently emphasised. Bauschinger states that ageing perfects the elastic properties in the direction of cold-working very soon. Scrutinising Bauschinger's and Muir's original data, it does not appear that with ageing they have ever reached a perfect elasticity in the direction in which the specimen was cold-worked, although the deviation from a straight line stress-strain curve was so little that they possibly disregarded it. As regards specimens which were cold stretched and subsequently tested in compression, the same law of ageing seems to hold, only the variations are much more marked. In either case, tension or compression, ageing or tempering, has the tendency to perfect the elastic properties of cold-stretched steel; however, while as regards tension, the stress-strain curve may in a few weeks become so nearly a straight line that it requires a very sensitive test to detect any lack of elasticity, as regards the compressive elastic properties, the amount of improvement necessary to reach perfect elasticity is so large that any shortcoming in it is inevitably detected.

In these experiments, everything seemed to point to the fact that tempering at low temperatures was equivalent to accelerating the effects of time.

Because time was lacking to allow specimens to age properly, curves on Diagram IX. were obtained from a commercially cold-drawn specimen.

By studying the records of the engineering shops of the University of Michigan, the author obtained a piece of $\frac{7}{8}$ -inch round steel, commercially called cold-rolled shafting, which was received at least six months ago. It appears safe to consider

this stock as cold-drawn, although the trade name may be cold-rolled. It is believed cold-rolling is rarely used except for stock over 3 inches diameter, and certainly not for stock as small as $\frac{7}{8}$ -inch diameter.

One specimen cut from this bar was heated to a red heat and allowed to cool in the air in order to obtain a state of metal corresponding to a hot-rolled bar. Curve No. 207(y) gives the stress-strain curve for this specimen. Curve No. 197(y) gives the stress-strain curve of the cold-drawn and aged steel as it was when the author obtained it, tested in tension, and curve No. 201(y) gives the stress-strain curve of a similar specimen tested in compression. It may be noticed how the elastic limit in compression, if anything, is a little above the original elastic limit.

Muir, in a paragraph quoted above, p. 15, incidentally gives results at variance with the results given here. It would seem, however, that his tests on elastic properties are inconclusive because, on the one hand, they were limited in number, and on the other hand the specimens were only $1\frac{1}{4}$ inch long—that is, too small for accurate work.

If the contentions set forth in this paper are correct, it would appear that the strongest evidence Rosenhain mentions against the validity of his favourite amorphous cement theory (p. 15 of this paper) is invalid, and Beilby's amorphous cement theory emerges better substantiated than ever.¹

THE EFFECTS ON ELASTICITY OF COLD-TWISTING ARE PROPORTIONAL TO THE DISTANCE FROM THE AXIS.

On Diagram I. curve No. 22(d) has the appearance of being approximately a mean between curves No. 25(d) and No. 27(d), and on Diagram II. curve No. 21(d) appears to be an average between curves No. 17(d) and No. 75(f). The natural explanation seems to be that in cold-twisting the outside of the bar is strained severely, and the effect of it on the elastic properties corresponds to curve No. 27(d), while at the centre of the bar the material is strained very slightly, and therefore its elastic properties remain approximately as shown by No. 25(d). When

¹ For a more detailed discussion of Beilby's amorphous cement theory, see pp. 24-27 of this paper.

a twisted bar is tested in tension, since its elastic properties vary from the centre to the outside, as from curve No. 25(d) to curve No. 27(d), the resulting curve will be a compromise between the two. If the amount of steel similarly strained was also directly proportional to the distance from the axis, a straight line curve could be expected for the tensile stress-strain curve of a cold-twisted bar. Since, however, the cross-sectional area of steel similarly strained varies as the square of the distance from the axis of the shaft, the curve to be expected is a second degree curve, which is borne out by the experiment. The curves in Diagram VII. were obtained to throw some light on this hypothesis. A $1\frac{3}{4}$ -inch round bar was cold-twisted 31.5 per cent. A specimen No. 72(j) was cut from the centre, and another specimen No. 73(j) was cut from the outside, of dimensions as shown on Diagram VII. The elastic limit of both specimens occurs at the same value as that of the original bar. Note that curve No. 73(j) runs not only higher than curve No. 72(j), but that the breaking stress of specimen No. 73(j) is 86,200 pounds per square inch, while the breaking stress of curve No. 72(j) is 69,800 pounds per square inch.

THE EFFECTS OF COLD-WORKING ON THE ELASTIC PROPERTIES OF STEEL ARE PROBABLY A FUNCTION OF THE STRAINS AND INDEPENDENT OF THE STRESSES INVOLVED IN THE COLD-WORKING PROCESS.

The interesting point as to whether the effects of cold-working, here discussed, are dependent on the stresses involved in the cold-working of the steel or are determined by the degree of deformation given to the specimen as the result of cold-working, cannot be fully determined from the results of this investigation. It seems certain, however, that the stresses set up in cold-working have little to do with the changes in elastic properties, and it seems likely that changes in elastic properties of steel are determined by the degree and kind of deformation given to the specimen in the process of cold-working, regardless of what stresses were involved in bringing these deformations about.

Diagram VIII. is intended to show the effects of cold-working on the elastic properties of steel in a direction at right angles

to the direction of cold-working. Curve No. 104(s) shows the stress-strain curve of the steel as received. Curve No. 98(s) shows the stress-strain curve of a specimen cut from the same bar and hammered cold, transversely, in a steam trip hammer, subsequently machined, and then tested in the direction of the longitudinal axis of the specimen. The stresses in the direction of the longitudinal axis of specimen No. 98(s), at no time during the cold hammering process, can have been tensile stresses. The elongative strains, however, in the direction of the longitudinal axis amount to approximately 11.5 per cent. It is seen that cold hammering at right angles to the axis produces effects on the elastic properties of steel in a direction parallel to the axis similar to those obtained by straining under pure tensile stresses. That the curve is not a perfectly straight line was to be expected, since the cold hammering effect, of necessity, differed in intensity throughout the specimen. With strains produced, therefore, which correspond to tensile strains, but unaccompanied by tensile stresses, the change of elastic properties corresponds to those produced by cold-stretching.

To determine whether the cold-working strains or cold-working stresses determine the ultimate elastic properties of cold-worked steel another test was made as follows. It is very noticeable that when a specimen of mild steel is stressed beyond the elastic limit, any amount up to the maximum stress, the beam drops as soon as the machine is stopped, indicating a continued rupturing of crystal grains under constant or slightly decreasing stresses. For example, when specimen (A) of original elastic limit of 32,000 pounds per square inch was stressed instantaneously to 58,500 pounds per square inch, it was found to have been strained 9.4 per cent. The machine was stopped and the beam immediately dropped, indicating that the specimen continued straining under a decreasing load. If it is desired to maintain a constant stress of 58,500 pounds per square inch on the specimen, it is found that the machine must be slowly turned by hand for several hours to keep the beam balanced with a constant load reading. This indicates that straining of the specimen continues for several hours if the steel is once stressed past the elastic limit and kept under a constant load.

Three specimens, A, B, and C, of the same bar were prepared. The original elastic limit of the steel was 32,000 pounds per square inch. Specimen A was stressed instantaneously to a stress of 58,500 pounds per square inch, and found to have been strained 9.4 per cent. Specimen B was stressed to a stress of 58,500 pounds per square inch, this stress kept constant for fifty minutes, when it was found to have been strained 12 per cent. Specimen C was stressed instantaneously to a stress of 61,000 pounds per square inch and found to have been strained 12 per cent. Specimens A and B were thus stressed the same amount, but strained differently. Specimens B and C were strained the same amount but stressed differently. The three specimens were boiled together and then tested in tension. Specimen A was found to have an elastic limit of 64,000 pounds per square inch, specimen B had an elastic limit of 67,000 pounds per square inch, while specimen C had an elastic limit of 67,000 pounds per square inch. Since specimens B and C, which were strained the same amount but stressed differently, had the same ultimate elastic limit, and specimens A and B, which were stressed the same amount and strained differently, had different elastic limits, it appears that the effect of cold-working on the elastic properties of the steel is a function of the strain and not of the stress.

Curves on Diagram VII. also indicate a raising of tensile or compressive elastic properties as the result of cold-twisting, without the presence of either tensile or compressive stresses in the direction of the axis of the specimen during the cold-working process.

FATIGUE.

Although no fatigue tests were made in this investigation, it may still be proper to call attention to the relation of the curves on Diagrams IV., V., and VI. to the problem of fatigue. A great many tests have been made on steel subjected to repeated stresses in one direction, and also with repeated stresses in opposite direction. Although all experiments agree in that steel fails under lower stresses when the stresses are repeated or reversed a great many times, some differ as to whether steel can be made to fail, even under reversed stresses, at stresses below the original

elastic limit. Possibly the difficulty in measuring the stresses or the neglect to consider the rate at which stress travels, may account for some differences of opinion. It is believed the curves on Diagrams IV., V., and VI. are the first to show accurately how the elastic properties of steel are affected under reversal of stresses within a comparatively short time after the steel has been stressed beyond the elastic limit.

ELECTRIC RESISTIVITY OF COLD-WORKED STEEL.

Four specimens cut from a hot-rolled mild steel bar, the chemical composition of which is given under (w) in Table I., p. 3, were cold-worked and subsequently tested for their electric resistivity by Professor Edward D. Campbell of the University of Michigan. The first specimen was tested "as received"; the second specimen was cold-strained 15 per cent. and incidentally stressed to a stress of 57,000 pounds per square inch; the third specimen was cold-compressed 10 per cent., and the fourth specimen was cold-twisted 40° in 1 inch. The electric resistivity for all four specimens was 13.87 microhms at 25° C., indicating that cold-working does not affect in any way the electric resistivity of steel.¹

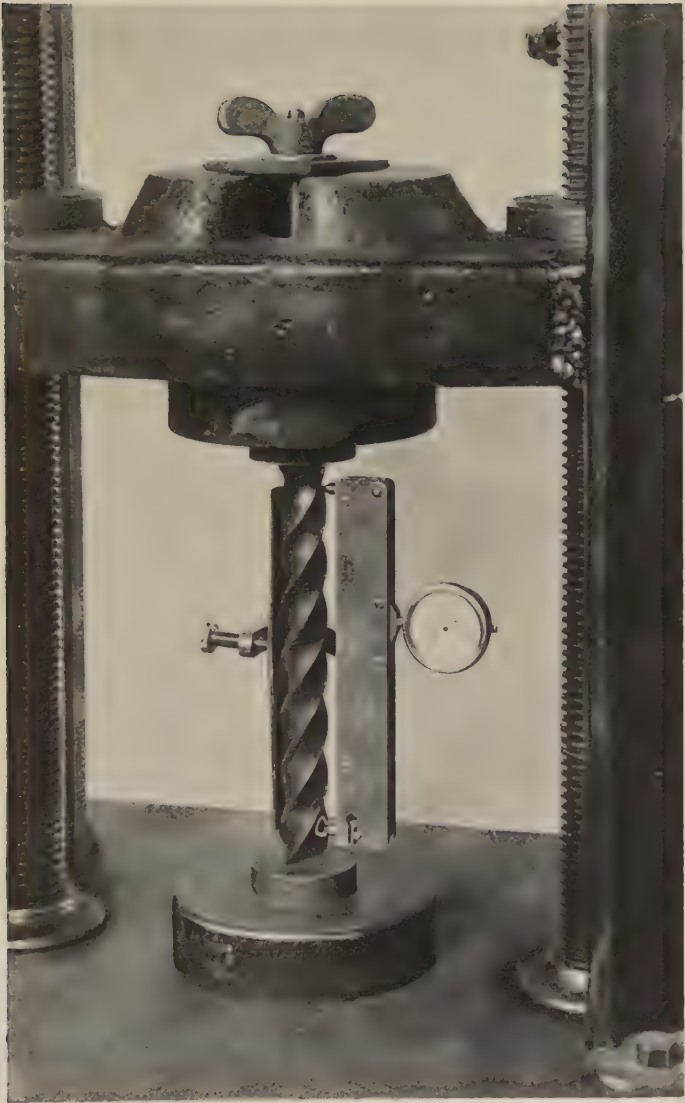
THE EFFECTS OF COLD-WORKING ON THE ELASTIC PROPERTIES OF ALLOY STEELS.

Bauschinger, Muir, and the author confined themselves very largely to studying the effects of overstrain on what might be designated as "mild steel." However, twenty-five different bars, many of them obtained from entirely different sources, were used for the tests discussed in this paper. Within the changes in chemical composition, in these twenty-five different sources of test specimens, no variance with the laws of the effects of cold-working on the elastic properties of steel could be detected.

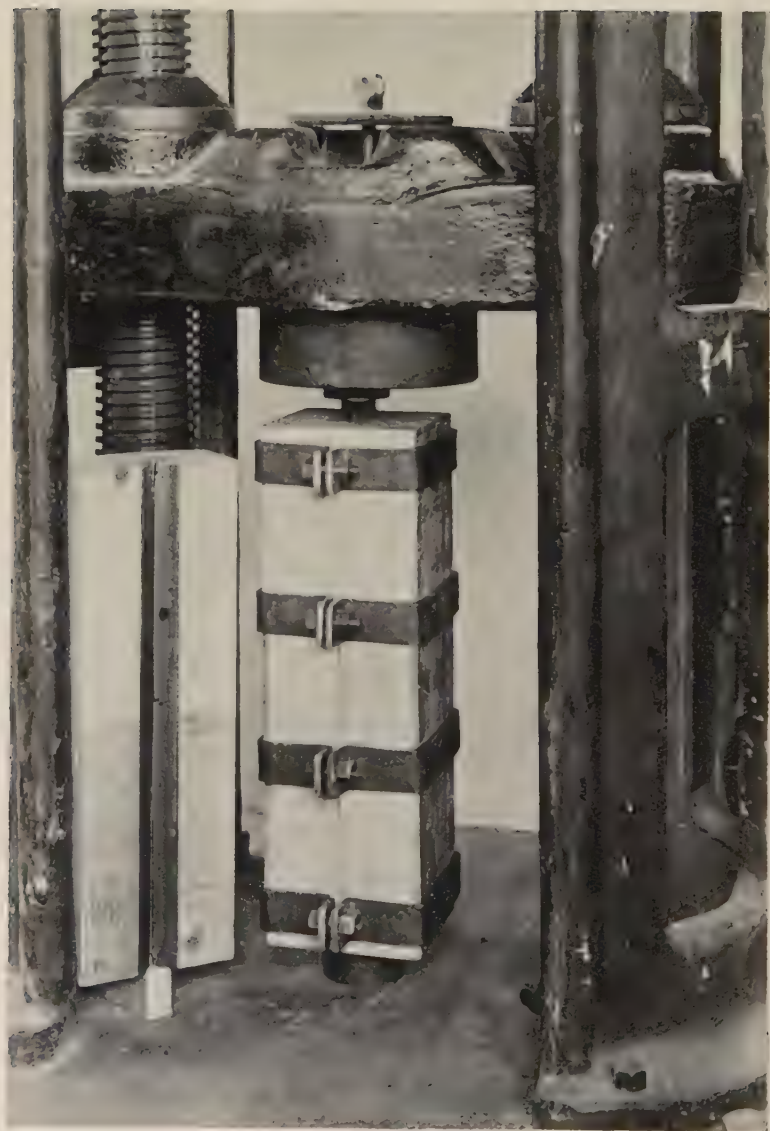
The only extensive work along this line on alloy steel seems to be the work that is being carried on by the U.S. Arsenal at Watertown, Mass.¹

¹ For a more detailed discussion of this test by Professor Edward D. Campbell, see Faraday Society of 1918; also articles on "Specific Resistance," *Journal of the Iron and Steel Institute*, 1915 and 1916.

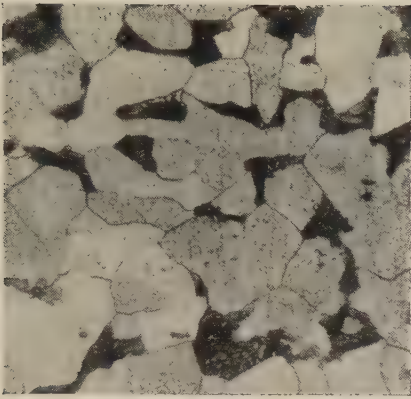
² "Test of Metals," 1915.



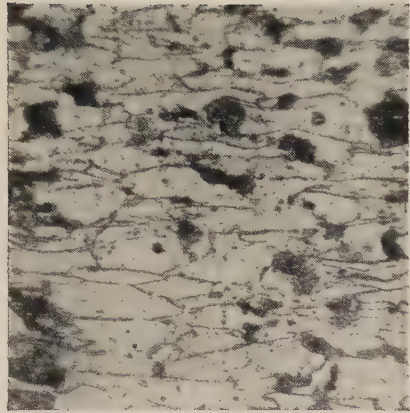
Compression Test Machine with Berry Strain Gauge.



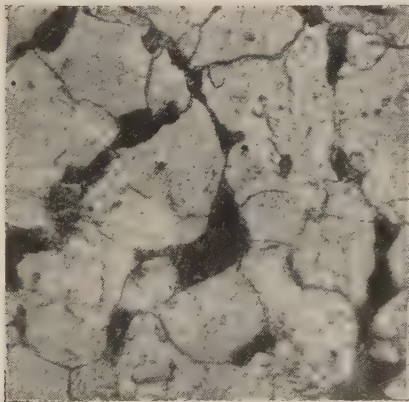
Riehle Tension and Compression Machine.



No. 1.—Longitudinal section of mild steel specimen used in specific gravity test, "as received" (p. 26).



No. 2.—Same steel cold compressed to half its original length.



No. 3.—Transverse section of same specimen, cold compressed.

All magnified 600 diameters, and reduced by one-third.

These tests were confined to a 3.25 per cent. nickel steel, and the results published to date seem to confirm the results presented in this paper. The yield point of a steel with an original elastic limit of 60,000 pounds per square inch is raised to 120,000 pounds per square inch. Since the Watertown Arsenal, to date, did not experiment with torsional tests or with cold compressed specimens, or with the effects of tempering in connection with ageing, no further comparisons can be made. It is shown, however, that to the maximum extent they have aged—namely, seven days, their resultant tests show an imperfect elasticity beyond the original value of the elastic limit of the specimen, just as was the case with specimens tested by the author.

LAW DEFINING THE EFFECTS OF COLD-WORKING ON THE ELASTIC PROPERTIES OF MILD STEEL.

Diagrams I., II., and III., and also Diagrams IV., V., and VI., reveal striking similarities which suggest that definite laws might govern the effects of cold-working upon the elastic properties of steel. If we distinguish the several kinds of elasticity and cold-working as being of different direction and sense, for example, tension and compression as of the same direction but opposite sense; positive torsion (+ shear) and negative torsion (—shear) as of one direction but opposite sense; but torsion (shear) and tension, respectively, as being of different direction, then we may say:

1. When mild steel is cold-worked and properly aged or tempered and subsequently tested in the same sense as that of the cold-working, its elastic limit may be raised more than 100 per cent. and from 10 to 20 per cent. beyond the stress at which cold-working was discontinued.
2. When mild steel is cold-worked in one direction and properly aged or tempered, but tested in either one of two senses of a different direction, then its elastic limit may be raised some 50 per cent.
3. When mild steel is cold-worked in one sense and properly aged or tempered but tested in the opposite sense, then the elastic limit remains at the value of the original elastic limit, but the yield point is raised.

4. When mild steel is cold-worked in any direction or sense and tested in any direction or sense, without any ageing or tempering, then the elastic limit falls below the value of the original elastic limit, often down to zero.
5. Tempering cold-worked steel at temperatures from 100° to 300° C., or ageing cold-worked steel, has a tendency to perfect its elastic properties. Tempering merely accelerates the effects of time.

The first part of this statement is exemplified by curves No. 25(d) and No. 27(d), Diagram I., curves No. 17(d) and No. 75(f), Diagram II., and curves K59 and K64, Diagram III., and by similar curves on Diagrams IV., V., and VI. The second part of the above statement is exemplified by curve K63, Diagram III., curve No. 143(v), Diagram VI., and curve No. 73(j), Diagram VII. The third part of the above statement is exemplified by curve No. 80(m), Diagram I., curve No. 77(d), Diagram II., and curve No. K65, Diagram III., No. 112(t), Diagram IV., No. 177(w), Diagram V., and No. 147(v), Diagram VI. The fourth part of the above statement is exemplified by curves No. 114(t), Diagram IV., No. 180(w), Diagram V., and No. 146(v), Diagram VI.

THEORY EXPLAINING THE EFFECT OF COLD-WORKING ON THE ELASTIC PROPERTIES OF STEEL.

It is hardly the purpose, in this paper, to review exhaustively the contributions to chemical and metallurgical science, of the last twenty years, bearing on the problem of cold-working steel. Certainly, however, to some, the striking improvements in steel as the result of cold-working appear mysterious. One is likely to presuppose that straining steel beyond the elastic limit injures steel permanently. It may not be amiss, then, to review briefly one of the theories advanced to explain the phenomena associated with cold-working of steel.

The amorphous cement theory was advanced by Beilby about 1903 and developed since, particularly by himself, Rosenhain, and Ewing. The following discussion and interpretation of it is made in the light of the facts established in this research.

Beilby and Rosenhain suppose that steel exists in two phases

—the amorphous phase and the crystalline phase. As steel crystallises, the size of the crystals are inversely proportional to the rate of cooling. Different crystals are differently oriented, and when they come together, some steel, encased between them, is unable to align itself with either one of the adjoining crystals. This steel remains in the amorphous state and cements the different crystals into one solid mass. This amorphous cement is supposed to be stronger than the crystalline steel. With a rapid rate of cooling the crystals are smaller, the amorphous cement, which coats all the crystal grains, is naturally greater in quantity and, as is well known, the elastic limit of rapidly cooled mild steel is higher than that of annealed mild steel. It has been shown that when steel is fractured the fracture takes place across a crystal and never along one of the crystal boundaries, which also supports the belief in the superior strength of the cementing material over the crystalline material. When a steel specimen is stressed increasingly, a stress value is reached at which the large crystals break up into smaller ones. This breaking up of the crystals marks the elastic limit of the steel. This breaking up of large crystal grains into smaller ones occurs along definite cleavage planes (slip bands). Naturally, the crystals oriented most favourably for breaking up along its cleavage planes are ruptured first, while the ones that are oriented less favourably to the direction of the particular stress applied are ruptured later when the stress has become higher. The internal work expended on the metal while being strained transforms some of the crystalline metal into amorphous metal. This amorphous metal hardens but is at first quite plastic. Therefore, when a specimen is stressed soon after cold-working, there is a constant yielding of the amorphous metal under a permanent stress, which makes the specimen as a whole yield more or less. When a specimen is stressed soon after cold-working in a direction opposite to the direction of cold-working, while the newly formed amorphous cement is still plastic, naturally the fractured crystals are tempted to slide back along the slip bands, as much as possible, to their original positions, and the specimen yields in a very pronounced way. This amorphous cement, however, hardens with time, and especially with the gentle application of heat. After a cold-worked specimen is aged, therefore, or boiled in water for fifteen

minutes, no plasticity of the specimen is observed. When tested after tempering in the same sense and direction as that of cold-working, most of the planes of weakness have yielded under the cold-working process and renewed breaking up of crystals does not commence, or in other words, the elastic limit is not reached until a stress has been reached higher than the stress at which cold-working of the specimen was discontinued. When a specimen is tested in the same sense but opposite direction from the direction in which it was cold-worked, but after the amorphous cement formed in cold-working has thoroughly hardened by tempering or ageing, breaking up of the crystals does not commence; or in other words, the elastic limit is not reached until after a stress equal to the original elastic limit has been exceeded.

Beilby, Rosenhain, and Ewing advance a great deal of chemical and metallurgical data in support of this theory that steel exists in two phases—amorphous and crystalline. One of the facts advanced is that amorphous steel has a lower specific gravity than crystalline steel, and that therefore cold-worked steel, because of its higher percentage of amorphous steel, has a lower specific gravity than “as received” steel.

MICROSTRUCTURE OF COLD-WORKED STEEL.

Regardless of the conclusions drawn from it, the fact that cold-working steel lowers its specific gravity has been well substantiated by independent investigators.¹ The author, also, has cold-compressed three specimens of mild steel 1 inch $\times$ 2 inches, and three specimens of tool steel $\frac{3}{4}$ inch $\times$ 1 $\frac{1}{2}$ inch to one-half their length, and found a reduction of specific gravity in each case, the average for the six specimens amounting to 0.225 per cent. Photo. No. 1, Plate III., gives a photomicrograph of the longitudinal section of one of the specimens of mild steel used in the specific gravity test “as received.” Photo. No. 2 gives a photomicrograph of a *longitudinal* section of the same specimen “cold-compressed” to half its original length. Photo. No. 3 gives a photomicrograph of a *transverse* section of the same specimen cold-compressed, and taken as near as possible to the

¹ F. C. Lea and W. Norman Thomas, “Change of Density of Mild Steel strained by Compression beyond the Yield Point,” *Engineering*, July 2, 1915.

point in the specimen where No. 2 was taken. The magnification of all three micrographs was 600 diameters.

It may be noticed on No. 2 how the individual grains have flattened as the result of compression, and correspondingly it may be seen on No. 5 of the transverse section, taken at the same point, how these same grains have spread. The actual breaking up of these crystals into smaller parts cannot be determined from these photographs. The rupturing of steel grains under stress along slip bands can be observed under the microscope when the specimen is prepared and polished in advance of the test and the specimen strained subsequently,¹ and under favourable circumstances it may be observed with the naked eye.² The fractures indicated by the slip bands are covered over if the specimen is polished after being strained, and they are too minute to be detected by the microscope upon subsequent etching of a polished specimen.

TESTS ON STEEL BALLS.

Another argument for the existence of amorphous steel was advanced by Beilby and Bengough, in explaining the phenomena of polishing steel by the formation of an amorphous cement on the surface of a steel specimen while being polished. Polishing steel consists of successive stages of grinding and scratching with an abrasive that is harder than steel. The ultimate result is a mirror face that even under a strong microscope does not reveal any scratches. Sometimes, after slight etching with a dilute acid, when some of the outside steel has been removed, scratches may be observed again, indicating that they were merely covered over with something. This something, according to Beilby, Bengough, and others, is amorphous steel worked up on the surface of the steel by the cold-grinding.

When first produced this amorphous steel is like a viscous liquid. It has a considerable surface tension which causes it to smooth out and even cover minute scratches or cracks. It acts similarly to a band of fresh paint. Just after removal of the brush the marks of the hairs are visible, but in a few seconds the

¹ Ewing and Rosenbain, *Philosophical Transactions of the Royal Society*, 353A, 1900.

² *Commission des Méthodes d'Essai des Matériaux de Construction, Rapports Particuliers*, tome ii., 1900.

surface tension in the fresh paint has caused the ridges to disappear and the paint to present a flat surface. This would thus explain the apparently anomalous fact that successive grinding operations on steel produce a surface which, even under a strong microscope, is free from any abrasive marks.

The polishing is thus a cold-working operation, the effect of which does not extend beyond the surface.

Because this amorphous steel produced on the surface by cold grinding and polishing is stronger and harder than the crystalline steel in the body of the specimen, it occurred to the author that cold ground and highly polished steel balls may exhibit differences in crushing strength when tested before and after polishing, or after amorphous cement is artificially removed by acid. The author is at present engaged upon a series of tests on steel balls, generously furnished by the Hoover Steel Ball Company of Ann Arbor, Michigan, the results of which it is hoped will be ready for publication soon. Although too early to discuss these tests here in detail, for the purpose of this paper, the following can be stated :

In the manufacture of steel balls the balls are forged, heat treated, rough ground, emery ground, and polished. As the result of two hundred crushing tests on 1-inch balls it was found that the rough ground balls, although slightly larger in size, were 25 per cent. weaker than the polished balls.

Upon etching polished balls for twenty minutes in boiling hydrochloric acid, 25 per cent. solution, their crushing strength decreased 32 per cent. Upon etching rough ground balls and polished balls in similar acid solutions, the same length of time, the crushing strength of the two came down to the same value, indicating that the reduction of crushing strength is not due to the effects of the acid, but rather due to the removal of the amorphous cement from the surface.

Although the amorphous cement theory might lead one to expect a quantitative difference in crushing strength between polished balls and balls which had their polish removed or else tested before they were polished, the author was sceptical before his tests, and expected the difference to be hardly noticeable. The difference of 30 per cent., indeed, seems phenomenal. It may yet be due to other causes which have not been detected. How-

ever, it should be borne in mind that although the amount of amorphous cement produced upon the surface of the steel balls by polishing is very little indeed, it is most advantageously placed to increase the crushing strength of steel balls.

The tests on steel balls were made in an especially designed machine, three balls being tested in line.

COMMERCIAL ASPECTS OF COLD-WORKING MILD STEEL.

One of the most desirable properties in steel is a high elastic limit coupled with a fair degree of ductility. Such high elastic limit is usually obtained by alloying steel or by heat treatment, or by a combination of both. However, any process tending to increase the elastic limit nearly always tends to decrease the ductility. In case of nickel steel, which gives a combination of high ductility and high elastic limit, the process of manufacture is expensive.

Possibly the most conspicuous feature of cold-worked mild steel is its high elastic limit coupled with its relatively high degree of ductility. Perhaps a few remarks should here be made about the best measure of ductility. Three different tests for ductility are ordinarily used—the bend test, the test to determine the percentage of elongation, and the test to determine the percentage reduction of area of the fractured specimens. The bend test is not satisfactory, because two specimens may be bent through an angle of 180° and close completely upon themselves and yet be ductile in very different degrees. Furthermore, a bend test is of no use except for very brittle steels, as a $\frac{3}{4}$ -inch round steel specimen 0.55 per cent. carbon, which behaves as a hard steel, may be bent to close upon itself, without developing cracks. The percentage of elongation test gives valuable information regarding ductility, but furnishes a poor standard, because on the one hand the results vary for different gauge lengths, and on the other hand the results are affected by the location of the point of fracture, viz. whether the fracture occurs on one of the gauge points, between gauge points or outside of the gauge points.

The percentage reduction of area after fracture can be measured regardless of size of specimen, and gives appreciable values when the percentage of elongation is often too small to be noticed.

The test for percentage of elongation naturally gives relatively small values for cold-stretched specimens, as most of the potential yielding is used up in the cold-stretching processes. Expressed in terms of percentage of reduction of area, cold-worked steel of an elastic limit of 70,000 pounds per square inch may have a reduction of area as high as 65 per cent. As regards the bend test, cold-worked steel of an elastic limit of 70,000 pounds per square inch may be bent double to close completely upon itself, without manifesting any tendency to crack, even in 1-inch square specimens.

The decrease of ductility is very noticeable in commercial cold-drawing of shafting and wires; but in this case the cold-working is excessive, and therefore it does not follow that with a more moderate degree of cold-working an elastic limit of 70,000 pounds per square inch, associated with a high degree of ductility, can be obtained.

Steel has been cold-worked commercially with the object of improving its elastic properties, as in the case of hoisting cables and cables for suspension-bridges. More often, however, cold-working is primarily resorted to for other purposes. Square reinforcing bars for reinforced concrete beams are cold-twisted for the supposed improvement in their bond properties. Wires and shafting are essentially cold-drawn because of the finished product it furnishes, true to size throughout.

Some tests on fifty reinforced concrete beams, made by the author in connection with this problem, varying in size from 4 inches $\times$ 6 inches $\times$ (4 feet 6 inches) to 6 inches $\times$ 12 inches $\times$ (8 feet 0 inches), have shown that when cold-stretched steel is substituted for ordinary mild steel, the strength of a reinforced concrete beam is increased 80 per cent.

In tests on similarly reinforced concrete beams, alternately reinforced with square bars of mild steel and with cold-twisted square bars, the beams reinforced with cold-twisted bars showed an increase of strength of 35 per cent. over the beams similarly reinforced with plain bars, the same percentage of steel being used in both cases.

If a high elastic limit is desired without the true finish associated with cold-drawing, cold-stretching may possibly be resorted to, which can unquestionably be accomplished with a

great saving in cost of operation over the cold-drawing process. The pickling of the steel and the maintenance of the dies are totally unnecessary for cold-stretching steel.

Cold-drawing gives a beautifully true product with a somewhat increased elastic limit in torsion, as is manifested by curves K63, Diagram III., and curve 143(v), Diagram VI. However, if a high elastic limit in shear is desired, as for instance in case of shafts, much better results can be obtained by cold-twisting than by cold-drawing, as shown by curves K64, Diagram III., and curve 183(v), Diagram VI. This is true particularly when shafts are used to transmit torque in but one direction. If used to transmit torque in both directions, cold-twisting and tempering still give superior results, as indicated by curve 147 (v), Diagram VI., but in that case the advantage is not so striking. However, it appears that a considerable percentage of modern shafts are designed to transmit torque in one direction only, and because of critical speed considerations the tendency often has been to use as light and flexible shafts as possible. If a light shaft is desired, therefore, as in the case of turbine or aeroplane shafts, may it not be possible to make use of the large increase in torsional elastic limit by cold-twisting, as is illustrated by curves K64, Diagram III., and curve 183(v), Diagram VI.?

When the perfection of the elastic properties, rather than the general increase of the yield point, is of special importance, it has been shown to be essential that cold-worked steel be tempered at temperatures not much less than that of boiling water.

One manufacturer of helical wire springs related that he was facing bankruptcy because of the large percentage of failures of his springs, until someone suggested to heat the springs in an oven. After heating the springs, which were manufactured of cold-drawn wire stock, they were able to pass the most severe tests for elasticity. Curves 143(v) and 144(v), Diagram VI., which are substantiated by several other tests, clearly show how such tempering perfects the elasticity in torsion of drawn wires.

Lastly, steel balls have been carefully studied with reference to chemical composition and heat treatment. It appears that cold-grinding affects the ultimate strength of steel balls as much as either of the two above-mentioned factors.

ANALYSIS OF THE COLD-DRAWING PROCESS.

The question is asked, "What are the effects of cold-drawing on steel?" It appears that, as far as the elastic properties of the specimen are concerned, the effects of cold-drawing are the same as those due to cold-stretching, and are thus illustrated by the several curves shown in this paper.

In experiments on copper bars, specimens obtained from identically the same stock were tested, hot-rolled, cold-stretched, and commercially cold-drawn. The last two tests gave very similar stress-strain curves.

As regards steel it was not possible to obtain the cold-drawing of pre-tested hot-rolled stock. Therefore, tests were made on cold-drawn steel, the same steel annealed, then this annealed steel cold-stretched and subsequently tested in tension. Again, the stress-strain curves obtained for the commercially cold-drawn steel and the same steel cold-stretched were essentially the same.

Nevertheless, painstaking metallurgical research has been directed towards the effects of cold-drawing on steel, and it has been found, for example, that the surface of a cold-drawn specimen exhibits a greater hardness than the centre, suggesting some essential difference between stretching a bar and cold-drawing a bar through a die.

The following interpretation of the process of cold-drawing is offered, which, considered in the light of what was said earlier in this paper about the effects of cold-working being a function of the cold-working strains and independent of the cold-working stresses involved, points out that the effects of cold-drawing on the elastic properties of steel are essentially the same as those of cold-stretching.

It is well known that straining any material in one direction will produce a corresponding strain in a direction at right angles. Poisson's ratio purports to give the relation between the two strains at right angles to one another.

Bridgman has shown, in discussing the results of his extremely valuable experiments in the Jefferson Laboratory at Harvard University,¹ how a steel bar may be ruptured in the direction

¹ "Breaking Tests under Hydrostatic Pressure and Conditions of Rupture," *Philosophical Magazine*, July 1912.

of its axis, by means of hydrostatic pressures acting at right angles to its axis only.

In cold-drawing, a bar is forcibly pulled through a die, as indicated by Fig. 1 (p. 4). The stress in the bar, being defined as the load divided by the area, viz. $\frac{P}{A}$, will be somewhat larger at section B-B than at section C-C, because while the load P is essentially the same at both places, the area A_B is slightly smaller at section B-B than its corresponding area A_C at section C-C. We have seen, however, as is most forcibly illustrated by Bridgman, that the elastic limit will be exceeded when a critical strain value is passed regardless of the co-existing stress value.

Although the stress conditions at section C-C may be less severe, the strain conditions at section C-C are the most severe in the bar, because a relatively high stress, $\frac{P}{A_C}$, is accompanied by very high compressive stresses acting normal to the axis of the bar. It has been pointed out how, when a specimen of mild steel is tested in tension and wedge grips are used, the elastic limit is passed, first in the ends of the specimen between the wedge grips. and from there progresses throughout the length of the bar.

In cold-drawing a very similar condition exists. The bar is strained beyond its elastic limit in the portion that is momentarily within the die. Its crystal grains are elongated very similarly to the way they would elongate under pure tension, the bar locally contracts and soon passes on beyond the outside of the die. There the side pressure is removed and the tensile stress $\frac{P}{A}$, without the aid of the normal pressure provided by the walls of the die, proves insufficient to strain the metal any further.

Thus cold-drawing becomes a continuous process. The die is so designed, determined entirely by the practice giving the best results, that the stress in the bar outside of the die is insufficient to permit of plastic flow of metal, while within the die, when the strain resulting from the direct pull is augmented by strains resulting from compression normal to the axis of the bar, plastic flow takes place.¹

¹ For a very interesting and authoritative paper on cold-drawing and its effects, see J. F. Tinsley, *Iron Age*, 1914, p. 1320.

THE EFFECTS OF COLD-WORKING UPON ELASTIC PROPERTIES OF STEEL ARE PERMANENT.

The doubling or even tripling of tensile or torsional elastic properties of steel, if enticing to the man commercially interested in steel, inevitably leads him to inquire into the permanency of these effects. Curves on Diagram IX., stress-strain curves of cold-drawn steel which was aged at least six months and probably many months more, give some idea as to the permanency of the effects of cold-working upon steel. They manifest a perfect and high elastic range. Incidentally, they show how the elastic limit of steel is inevitably reduced to its original value upon heating it above the critical temperature and allowing it to cool in air. Possibly the most emphatic argument for the permanency of the beneficial effects of cold-working steel is found in the continued use of cold-worked steel during generations. It is stated that the Brooklyn bridge, constructed in 1872, made almost throughout of cold-drawn wires, is permitted to be stressed at present at least to double the stresses for which it was designed, based upon the reports of various technical commissions. Cold-rolled shafting has been used for a great many years, and helical springs are preferably made of cold-drawn wire. Never, in such cases, has a loss of elastic properties been noticed with time. Although the merits of the square twisted reinforcing bar is a matter under dispute, it is never even intimated that its elastic properties may be deleteriously affected with time.

In conclusion, the author desires to express his appreciation of the advice and encouragement received from Professor W. C. Hoad and Professor Edward D. Campbell of the University of Michigan, in carrying out his investigations, as well as his indebtedness to Mr. L. S. Cope, Metallurgist of the Hoover Steel Ball Company of Ann Arbor, Michigan, for the preparation of micrographs Nos. 1, 2, and 3, and for his liberal supplies of steel balls for the ball tests.

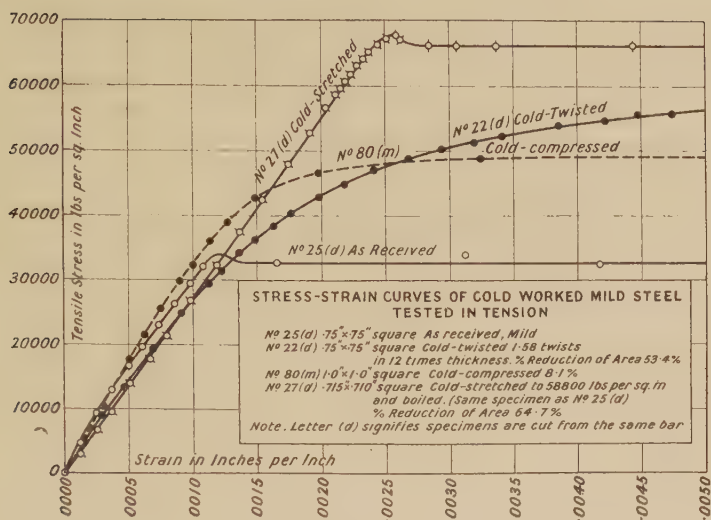


DIAGRAM I.

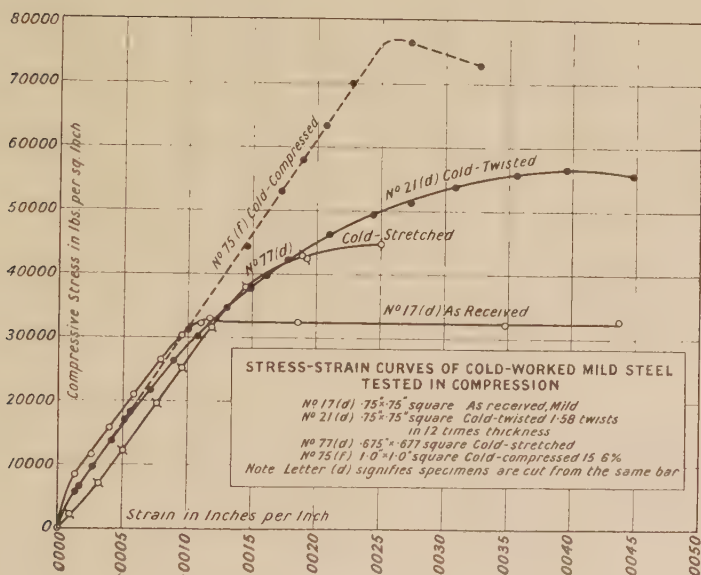


DIAGRAM II.

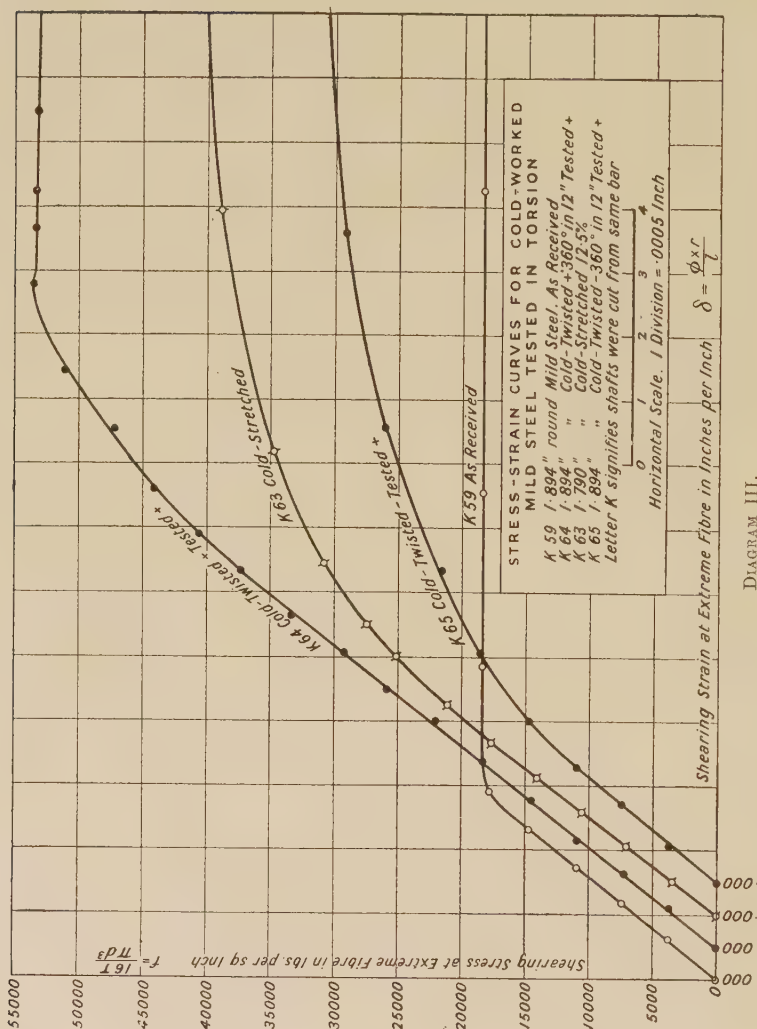


DIAGRAM III.

STRESS-STRAIN CURVES OF COLD WORKED
MILD STEEL TESTED IN TENSION
*Showing the effect of aging & tempering on the
elastic properties of cold-worked mild steel.*

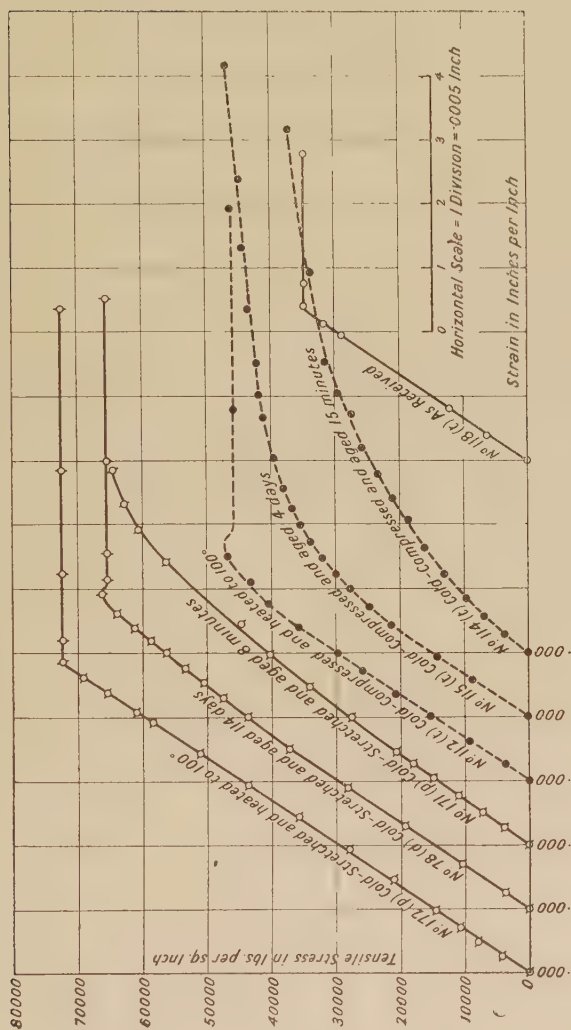


DIAGRAM IV.

STRESS-STRAIN CURVES OF COLD-WORKED
MILD STEEL TESTED IN COMPRESSION
*Showing the effect of aging & tempering on the
elastic properties of cold-worked mild steel.*

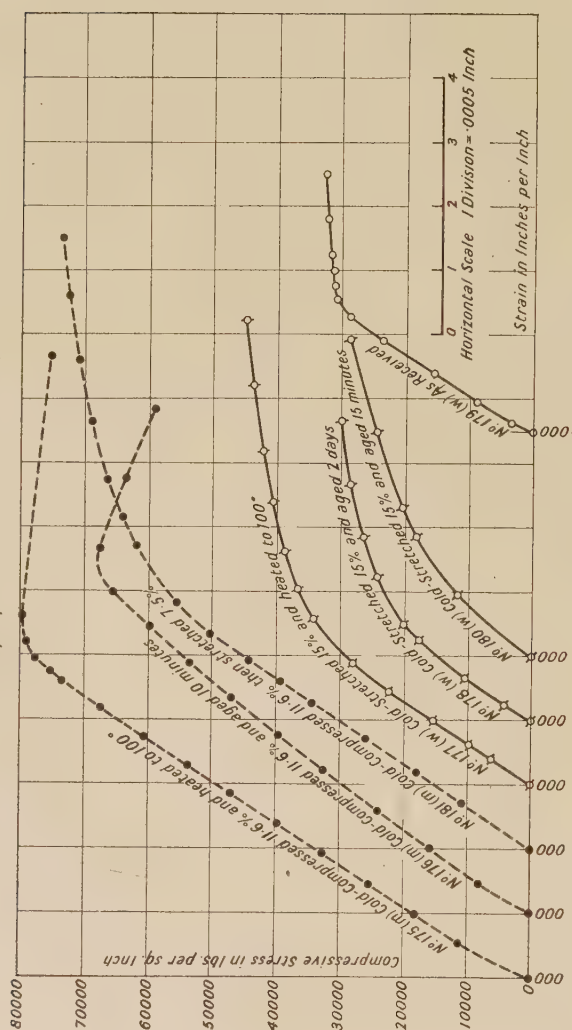


DIAGRAM V.

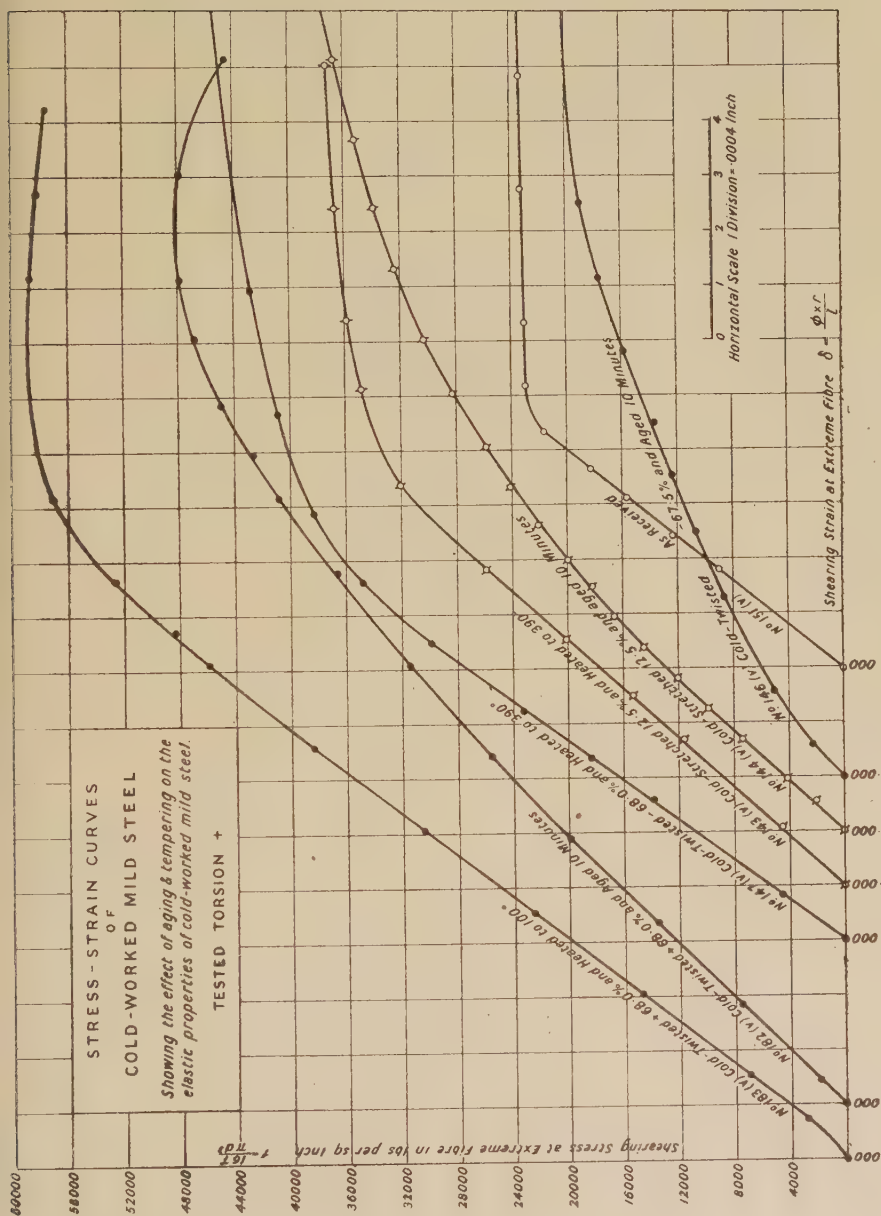


DIAGRAM VI.

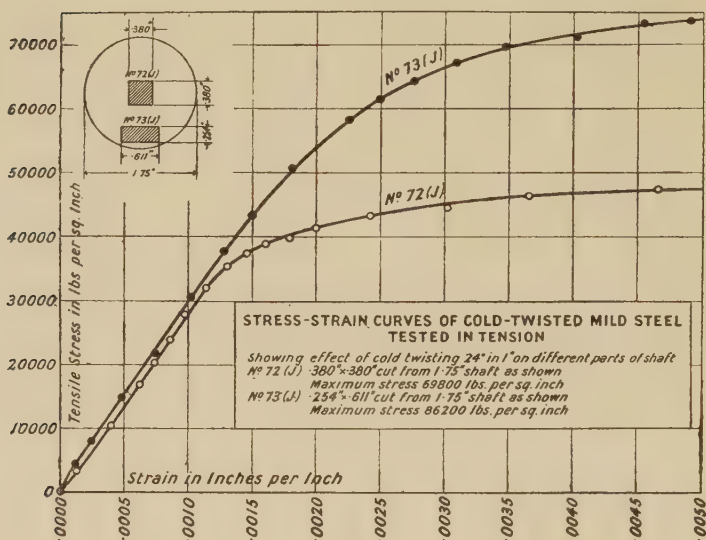


DIAGRAM VII.

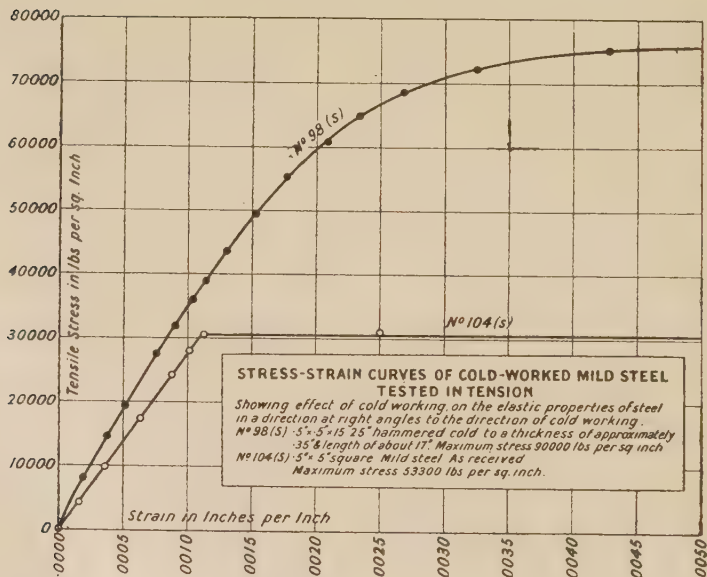


DIAGRAM VIII.

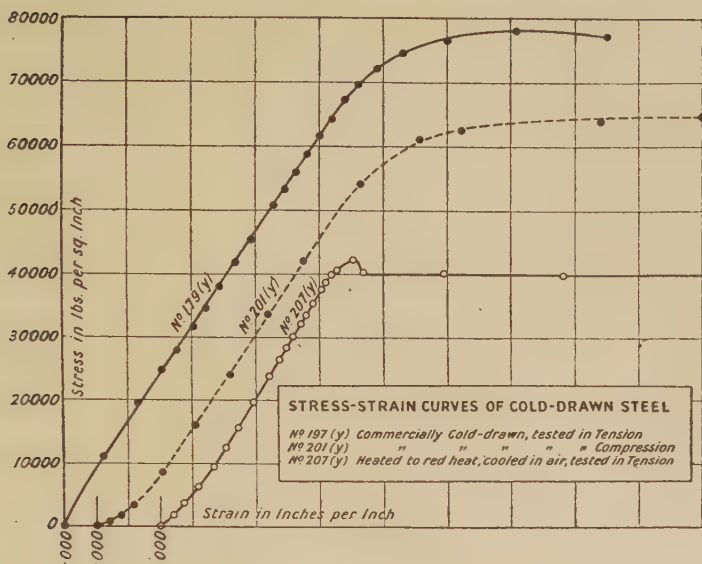


DIAGRAM IX.

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